J7

NASA TECHNICAL MEMORANDUM

NASA TM X-52640

NASA TM X-52640

LOW-NOISE PROPULSION SYSTEMS FOR SUBSONIC TRANSPORTS

by James J. Kramer, Bruce R. Leonard,
and Charles E. Feiler
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Symposium on Machinery Noise sponsored by the
American Society of Mechanical Engineers
Los Angeles, California, November 16-21, 1969

LOW-NOISE PROPULSION SYSTEMS

FOR SUBSONIC TRANSPORTS

by James J. Kramer, Bruce R. Leonard,
and Charles E. Feiler

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

Symposium on Machinery Noise
sponsored by the American Society of Mechanical Engineers
Los Angeles, California, November 16-21, 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LOW-NOISE PROPULSION SYSTEMS FOR SUBSONIC TRANSPORTS

by James J. Kramer, Bruce R. Leonard, and Charles E. Feiler

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

E-5194

ABSTRACT

A brief review of the preliminary design studies which led to a definition of specifications for a low-noise output turbofan engine for use on long-range subsonic transport aircraft is presented. Data on low-speed fans with and without acoustic treatment in the fan ducting are presented. These data indicate that overall noise output of four-engine long-range transport aircraft can be reduced 20 perceived noise decibels by appropriate fan design and the use of nacelle acoustic treatment.

INTRODUCTION

In 1967, the NASA initiated a research program to find out how to reduce the noise output of subsonic transport aircraft. A major element in this effort is directed at building and testing an experimental engine called the Quiet Engine. The amount of quieting desired was the maximum possible but noise levels at least 15 to 20 PNdB (perceived noise decibels) lower than the levels generated by today's jet fleet were the objectives. In order to compare levels it is necessary to use certain reference locations for observation of noise generated by over-flying aircraft. At the time these studies were begun the popular reference locations were under the flight path three statute miles from brake release on takeoff and one statute mile from touchdown on approach (Fig. 1). The current four engine aircraft

TM X-52640

(707 and DC-8) generate about 120 PNdB of noise at these locations when taking off in a fully-loaded condition and during landing. Thus, the study searched for an installed propulsion system that would generate no more than 100-105 PNdB when used on four engine aircraft. It was planned that this decrease in noise would be obtained through changes in the engine design and through the use of acoustically treated inlet and exhaust ducts. Throughout the study the use of power cut-backs to reduce the noise level during climb-out was not considered.

The prime noise sources considered were the fan and the exhaust jet. In the case of the fan, the noise is generated within the engine envelope. Thus, not only can the noise generated be reduced by appropriate design, but also the noise can be suppressed after it is generated and before it is radiated away from the engine by the use of absorptive liners in the ducting upstream and downstream of the fan.

In the case of the jet, the noise is generated as the high velocity exhaust flow mixes with the surrounding atmosphere. This mixing process occurs outside the engine envelope. Experiments on jet suppressors of reasonable size attached to the engine have shown only a limited effect on this mixing process and hence their noise reduction capability is limited. In order to achieve the noise levels desired for the Quiet Engine, the engine cycle was selected so as to result in sufficiently low jet velocity levels that the desired jet noise levels could be achieved without suppression.

In this paper, the Quiet Engine design studies will be reviewed. Some overall results of experiments to determine the acoustic behavior of fans and suppressors appropriate for use with a Quiet Engine will be presented.

EXPERIMENTAL QUIET ENGINE

The low jet noise levels dictated the use of a moderately high-bypass-ratio turbofan engine. The choice of bypass ratio and other specific engine design and cycle parameters is discussed in Refs. 1 and 2. These characteristics were developed during the preliminary design studies (Refs. 3 and 4) for the Quiet Engine and are listed in Table I. The thrust level of the engine was determined as that compatible with use on the 707/DC-8 type aircraft. Studies of the use of this engine on the DC-8 were conducted by McDonnell-Douglas and reported in Ref. 5. The study engines designed by Pratt & Whitney Division of United Aircraft Corporation and Allison Division of General Motors Corporation are shown in Figs. 2 and 3.

Both engines employ single-stage fans operating at tip speeds of the order of 1000 feet per second at takeoff power. These fans are driven by five-stage turbines. The compressor in the P&W engine is a single-spool twelve-stage device with five vane rows variable. The Allison compressor has sixteen stages on two spools with no variable vanes. Estimated engine weights are comparable in the neighborhood of 5000 pounds.

The fan noise output of these engines is estimated to be such that a four-engine transport would produce about 105PNdB during takeoff and landing for observers at the reference locations. These values are for engines installed in the aircraft without nacelle acoustic treatment. These engines are designed such that the noise levels are less than 95 PNdB at the reference locations. This jet noise floor will therefore dictate the level to which the fan noise can be reduced with added benefit for observers. Thus, the fan noise can be reduced an additional 10 PNdB by design of the fan or

by the use of absorptive liners without encountering the jet noise floor.

Following the preliminary design studies, NASA requested proposals for the detailed design, fabrication, test, and delivery of experimental engines satisfying the design constraints of Table I. A contract was let with the General Electric Co. in July 1969. The General Electric engine, shown in Fig. 4, makes use of the core of the CF-6 engine. This engine is now being detail designed. The design will be reviewed at the end of 1969. If the option to proceed into the engine fabrication and test phase is exercised, component testing will begin in 1970 leading to engine testing in 1971. A test engine will be delivered to NASA in mid-1972. At that time the engine will mated with an acoustically designed nacelle to result in a propulsion system incorporating the best available noise control technology.

FAN NOISE RESEARCH

In order to make the engine indeed quiet, it is necessary to demonstrate that the predicted fan noise levels can be achieved or made even lower. Thus, acoustic research on fans appropriate for use on a Quiet Engine is an important part of the total Quiet Engine program.

Both single-stage and two-stage fans are being examined in the fan noise research program. The single-stage fans are more attractive from the standpoint of minimum engine weight and size. However, it is feasible to use two stage fans in engines designed for this application as discussed in Refs. 3 and 4. Therefore, both types of fans are being investigated for possible acoustic advantages. The single-stage fans are being tested with both untreated and acoustically treated inlet and exhaust ducts.

Two-Stage Fans

In order to determine the acoustic performance of a two-stage fan of the size and pressure ratio required for use in an engine of the general character considered in Refs. 3 and 4, a General Electric TF-39 engine was modified and its acoustic performance determined. Details of this fan are presented in Ref. 6. In brief, the fan tested as part of the engine was a well-developed two-stage machine designed to produce an overall pressure ratio of approximately 1.5 at a tip speed of 1000 feet per second. The blade loading on both stages was moderate, well within current state-of-the-art design limits. Blade rows were spaced at least one chord length apart for noise considerations. The noise results are reported in detail in Ref. 6. Perceived noise levels as a function of angular position about the engine are shown in Fig. 5 for two rotative speed conditions corresponding to takeoff and approach power settings. Overall equivalent four engine aircraft flyover noise levels at the reference locations were calculated from these data as 112 PNdB during takeoff and 116 PNdB during approach. These levels are significantly higher than the desired levels for the Quiet Engine.

Single-Stage Fans

In order to determine the acoustic performance of single stage fans, a fan acoustic test facility was designed, built and is now in operation at the Lewis Research Center. The purpose of this facility is to obtain basic fan noise information and to establish the fan configuration for a quiet engine.

The facility is located adjacent to the main drive motor building of the Lewis 10×10 Supersonic Wind Tunnel. A drive shaft is coupled to the drive motors, penetrates the building wall, goes through a 4.25 to 1 speed increaser, and extends 47 feet beyond the building to the research fan rig. The drive shaft and research rig are supported on a concrete viaduct which is three feet wide and the center line of the rig is 18 feet above grade level to reduce ground effect (see Fig. 6).

An array of 16 microphones is used to gather acoustic data. They are 18 feet above grade, the same elevation as the rig centerline. Microphones are placed 10° intervals with the first microphone in front of the fan inlet and on a line which forms a 10° angle with the shaft centerline (see Fig. 7). It was desired that all microphones be on 100 feet radii with the terminus at the center of the fan rig, as are microphones 7 through 17. However, microphones 1 through 6 are at 10° intervals on a straight line perpendicular to the drive shaft and 31.5 feet in front of the fan. This arrangement was necessary because of the location of the drive motor building relative to the microphones. The readings from these microphones are corrected to 100 foot radii. The drive motor building wall has been treated with six inches of open-cell polyurethane foam to reduce the reflected noise to acceptable levels. The treatment can be seen on the lower half of the wall in Fig. 6. Signals from the microphones are simultaneously amplified and recorded on magnetic tape from which are obtained total sound power levels, one-third octave and narrow-band spectral data.

The first fan model (Fig. 8) to be tested has a single-stage rotor, 6 feet in diameter designed to absorb 23 000 horsepower at a cruise design cor-

rected speed of 3533 rpm. At its cruise design point the fan should produce a pressure ratio of 1.54 with air flow of 873 pounds per second. There are 53 rotor blades made from T651 aluminum, which are 18 inches long (hub to tip radius ratio of 0.5) with a mean chord of 5.5 inches.

The rig was designed, for acoustic reasons, with no inlet guide vanes and with approximately 4 rotor chord lengths spacing between the rotor blades and exit stator vanes (see Fig. 9). There are no part-span dampers on the rotor blades. The rotor tip speed at the cruise design point was selected to be 1110 feet per second. This value was a compromise between considerations of good noise performance (lower speed) and good aerodynamic performance (higher speed). This low tip speed requires a high blade loading in order to maintain the desired pressure ratio. The pressure ratio was selected to be a constant 1.54:1 along the blade span and the diffusion factor increases from 0.46 at the hub to a maximum of 0.54 at three-quarter span and then decreases to 0.44 at the tip. The blade camber line turns 19.9° past axial at the hub. The mean aspect ratio of the rotor blades is 3.1. The rotor solidity varies from 2.49 at the hub to 1.34 at the tip.

The number of stator vanes is 112, slightly greater than twice the number of rotor blades. The material is 17-4 stainless steel and the length of the vanes is 13.9 inches with a chord of 2.67 inches. The mean aspect ratio of the stator vanes is 5.2. The stator solidity varies from 2.39 at the root to 1.40 at the tip.

Base line data for the hard or untreated nacelle was obtained during the first test series. The fan was operated with both a long (101 in.)

and short (60 in.) inlet cylindrical section and with exhaust nozzles with flow areas equal to 1895, 2150, and 2435 square inches. The 1895 square inch area nozzle was the standard calculated for the design point weight flow. Results presented in this paper are for the short inlet with the 1895 square inch flow area nozzle.

The variation in perceived noise level as a function of angular position about the fan is shown in Fig. 10. The data are shown for the fan operating at various speeds from 60 to 90 percent of design speed. These data were corrected to a 100-foot radius and standard day conditions. The maximum levels occur at the 40^{o} position in the front quadrant and at the 140^{o} position in the rear quadrant.

In Figs. 11 and 12 the frequency spectra observed at these angular positions are displayed. Sound power levels as a function of one-third octave band center frequency are shown for 60, 70, 80, and 90% speeds. These data are for the same test configurations as the data of Fig. 10. For the 60 and 70 percent speed conditions the blade passing frequency falls in the one-third octave band with a 2000 Hz center frequency. For the 80 and 90 percent speed conditions the blade passing frequency moves to the next higher one-third octave band centered at 2500 Hz. The peak corresponding to the first harmonic of the blade passing frequency is clearly discernible as the relatively high reading one octave above the blade passing frequency. The lower frequency readings are consistently higher for the 140^{o} position than for the 40^{o} position. The low frequency levels are a consequence of the fan exhaust jet mixing with the atmosphere. Above 1000 Hz the levels are determined by the fan generated

noise. The levels above 1000 Hz observed in the front quadrant (40^o) are higher than those in the rear quadrant (140^o). This result was entirely unexpected. Most observers report higher readings in the rear quadrant. The difference in levels as reported by others is caused primarily by the convective effect on the sound of the overall air flow. In the LeRc fan test facility, the flow into the inlet bell-mouth is distorted by the presence of the concrete support structure and the shaft and its bearing pedestals. Various tests are in process to improve the inlet flow conditions in order to check the validity of the hypothesis that this distorted inlet flow is the cause of the higher than expected noise levels in the front quadrant.

If the takeoff fan speed (90% of design speed) data are used to calculate a four-engine aircraft flyover noise level at the expected altitude over the three-mile point (1000 ft), a value of 105 PNdB is obtained. The corresponding value for approach conditions (60% of design speed, 370 feet altitude) is 106 PNdB.

Fan Noise Suppressors

As discussed previously, fan noise output can be reduced by proper fan design and by the use of absorptive liners in the inlet and exhaust ducting. The fan noise test facility previously described will be used to test a series of suppressors suitable for use in the fan inlet and exhaust ducting of high bypass ratio engines such as the Quiet Engine. The first such model in this series has been designed, built and tested. The inlet and exhaust duct suppressors were designed according to the theory described in Ref. 7. This theory predicts the effects of wall impedance

and duct passage height and length on sound attenuation. Input information needed for the design calculation are the sound pressure level and frequency spectrum produced by the fan. The suppressors were designed before the acoustic test results on the single-stage fan model were available. Therefore, these data were estimated for the fan using the correlations of Ref. 8. The wall impedance required for a desired amount of attenuation with a specified duct passage height and length and noise source characteristics was determined by the method of Ref. 7. After establishing the impedance characteristics desired for the wall, it is necessary to translate these characteristics into a material-cavity arrangement that will provide them. The perforated plate-backing cavity combination used can be described as an array of Helmholtz resonators. The backing cavity is partitioned by an aluminum honeycomb into 3/8 inch hexagonal cells. There are correlations available in the literature that enable the impedance of such an array to be calculated. The important parameters describing the impedance are the hole diameter, plate thickness, open area ratio and backing cavity depth. The overall suppressor geometry is shown in Fig. 13 along with the values of the design parameters for each treated surface. As shown in the figure, opposing passage walls are treated differently. The intent of this design was to obtain attenuation over a broader frequency range than would be possible with the same treatment on each wall. A cross-sectional view of one of the splitter rings having this dual treatment is shown in the photograph of Fig. 14. The assembled inlet suppressor is shown in Fig. 15.

Due to the shape of the fan drive shaft housing, the length of the splitter rings decreases as the radius decreases. The passage heights and lengths were chosen such that the passages should provide about equal attenuation. The passage height and, therefore the number of rings, was selected such that the ratio of passage height to wavelength of the peak frequency was approximately two. The total treated surface area in the inlet is 254 square feet. The overall length-to-diameter ratio of the inlet duct is approximately 0.8. The inlet rings were cylindrical surfaces. No attempt was made to optimize the shape of the rings for aerodynamic purposes except at the leading and trailing edges.

Both the outer and inner walls of the exhaust duct were treated. The considerations entering into the design of the exit duct were the same as those in the inlet duct. This configuration of the exhaust duct had 216 square feet of treatment.

In Fig. 16, results indicating the performance of the acoustic treatment are presented. Maximum sound pressure levels without acoustic treatment were observed at the 40^{o} and 140^{o} angular positions. Frequency spectra of the noise at these locations are shown with and without the acoustic treatment for two fan speeds, 90 and 60% of design speed. These percentage speeds correspond to the fan speeds during takeoff and approach conditions.

For the takeoff fan speed conditions (90% of design speed), substantial reductions occur at frequencies above 300 Hz and continue through the audible range of 10 kHz. At the 40^{o} location where the jet mixing noise is not significant, significant attenuation is observed below 100 Hz. The

overall perceived noise level is reduced from 126 to 110 PNdB at the 40^{o} location on a 100-foot radius and from 122 to 113 PNdB at the 140^{o} location. The corresponding maximum levels of fan noise for a four-engine airplane takeoff flyover at the three-mile point are 105 PndB untreated and 91 PNdB with acoustic treatment.

With the fan operating at a speed typical of approach conditions (60% of design speed) similar trends are observed. The perceived noise levels are reduced 14 PNdB at the 40^{o} location and 11 PNdB at the 140^{o} location. For a simulated four-engine aircraft on landing approach over the one-mile point, the fan noise level will be 91 PNdB based on these data.

CONCLUDING REMARKS

Preliminary engine design studies have been completed for a low noise output turbofan engine. Experimental engines are now in the process of detailed design. Experimental results on single-stage fans of the character required for a Quiet Engine indicate acoustic performance close to that predicted in the preliminary design studies. In addition, noise-suppressing liners for fan inlet and exhaust ducts have been tested which result in at least 10 PNdB decrements in fan noise along a sideline. Based on the test results to date, it is expected that these engines will have acoustic performance such that four-engine aircraft will generate less than 100 PNdB for ground observers at the three-mile point during takeoff and at the one-mile point during landing.

1. J. F. McBride, "Quiet Engine Program Preliminary Design and Aircraft Integration," Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968, pp. 263-272.

2. J. J. Kramer, "Quiet Engine Program Detailed Engine Designs," Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968, pp. 273-285.

3. J. H. Lewis, III, "Quiet Engine Definition Program," Pratt and Whitney Aircraft Report PWA-3516, Vols. 1-5 (NASA CR-72457, Vols. 1-5), October 4, 1968.

4. Anon., "Quiet Engine Definition Program," General Motors Corp. Report FDR-5996 (NASA CR-72458), September, 1968.

5. R. E. Pendlay, "The Integration of Quiet Engines with Subsonic Transport Aircraft," NASA CR-72548, April, 1969.

6. R. E. Motsinger, et al., "Low Tip Speed Fan Noise Demonstration Program," General Electric Co. Report R68AEG482 (NASA CR-72456), 1968.

7. E. J. Rice, "Attenuation of Sound in Soft Walled Circular Ducts," presented at the Symposium on Aerodynamic Noise, Toronto, Canada, May 20-21, 1968.

8. J. T. Smith and M. E. House, "Internally Generated Noise from Gas Turbine Engines, Measurements and Predictions," ASME Paper No. 66-GT/N-43, 1966.

TABLE I. - QUIET ENGINE DESIGN CHARACTERISTICS

Engine	
Bypass ratio	5 to 6
Cruise thrust, lb	4900
Takeoff thrust, lb	22 000
Fan	
Number of stages	1
Inlet guide vanes	none
Spacing between rotor and stators	2 rotor chords
Tip speed, takeoff; ft/sec	1000
Tip speed, cruise; ft/sec	1100
Pressure ratio, cruise	1.5 to 1.6
Compressor	
Rotors	1 or 2
Maximum pressure ratio per rotor	12.5
Turbine	
Inlet temperature, takeoff; $^{\circ}F$	2000
Inlet temperature, cruise; $^{\circ}F$	1775

E-5194

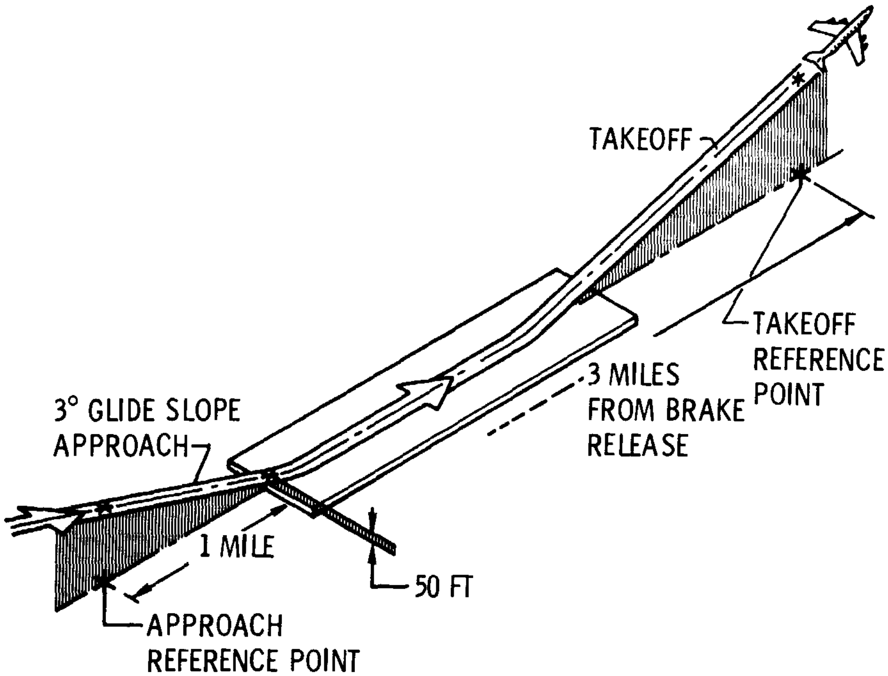
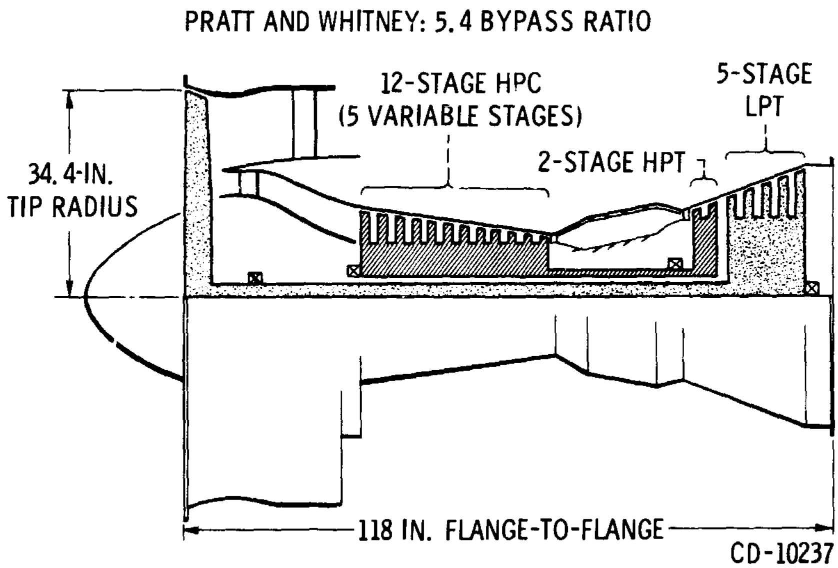


Figure 1. - Reference locations for flyover noise observation.



CS-47897

Figure 2. - Cross-section of preliminary design version of Quiet Engine by Pratt and Whitney Division of United Aircraft Corporation.

E-5194

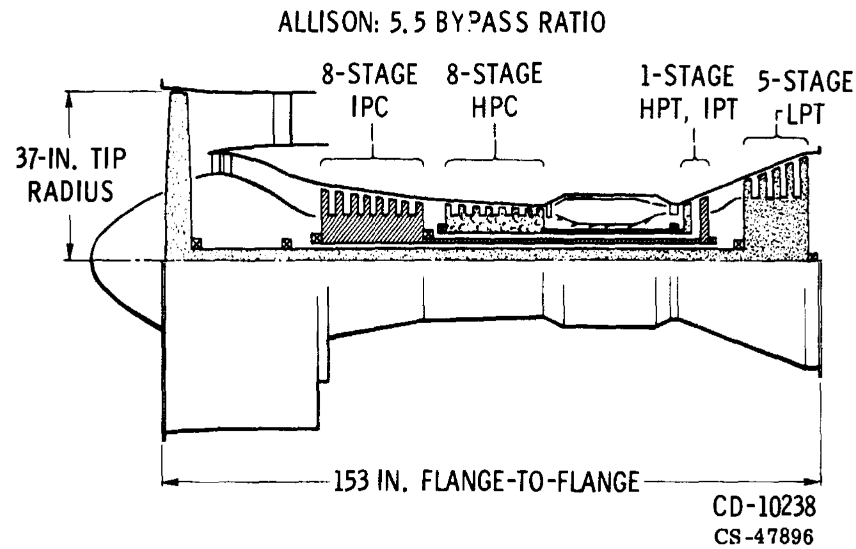


Figure 3. - Cross-section of preliminary design version of Quiet Engine by Allison Division of General Motors.

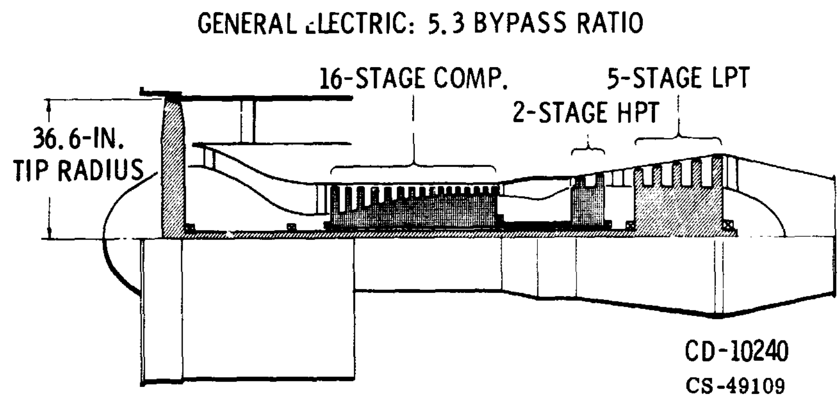


Figure 4. - Cross section of preliminary design version of Quiet Engine by General Electric Company.

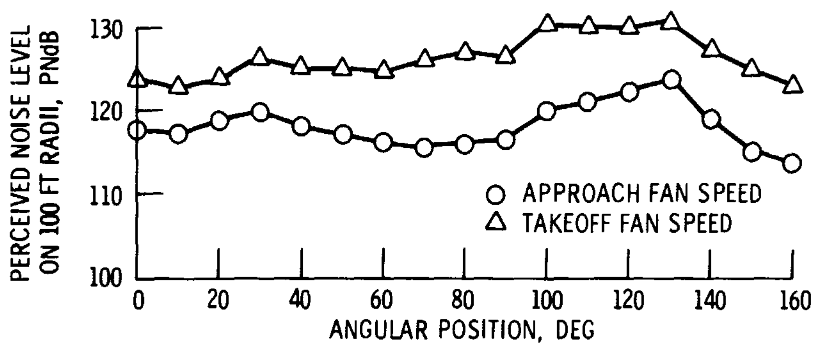
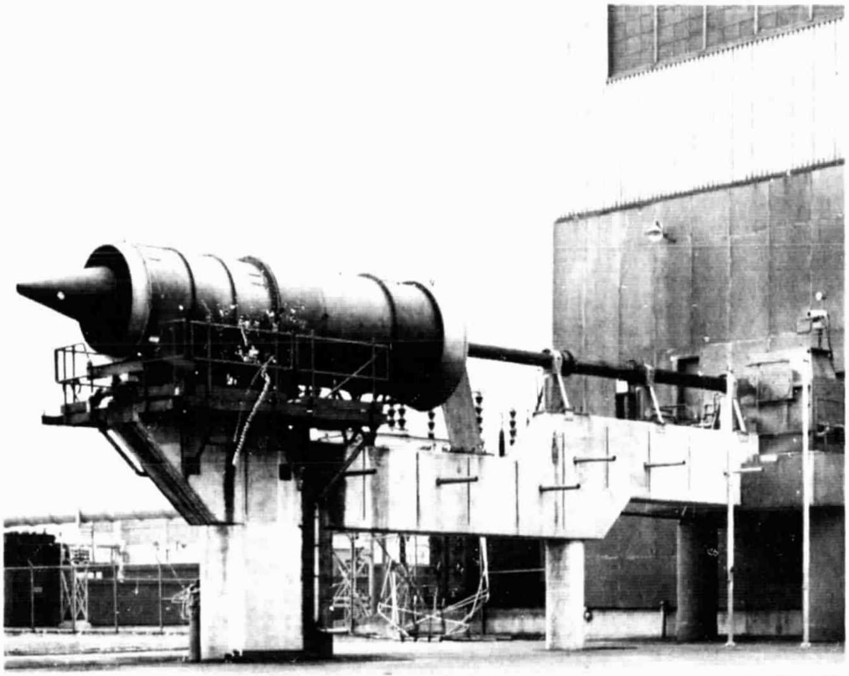


Figure 5. - Perceived noise level as a function of angular position (100 ft radius) of a modified TF-39 engine with a two-stage low-tip-speed fan.

E-5194



C-69-862

Figure 6. - Large-scale fan acoustic test facility.

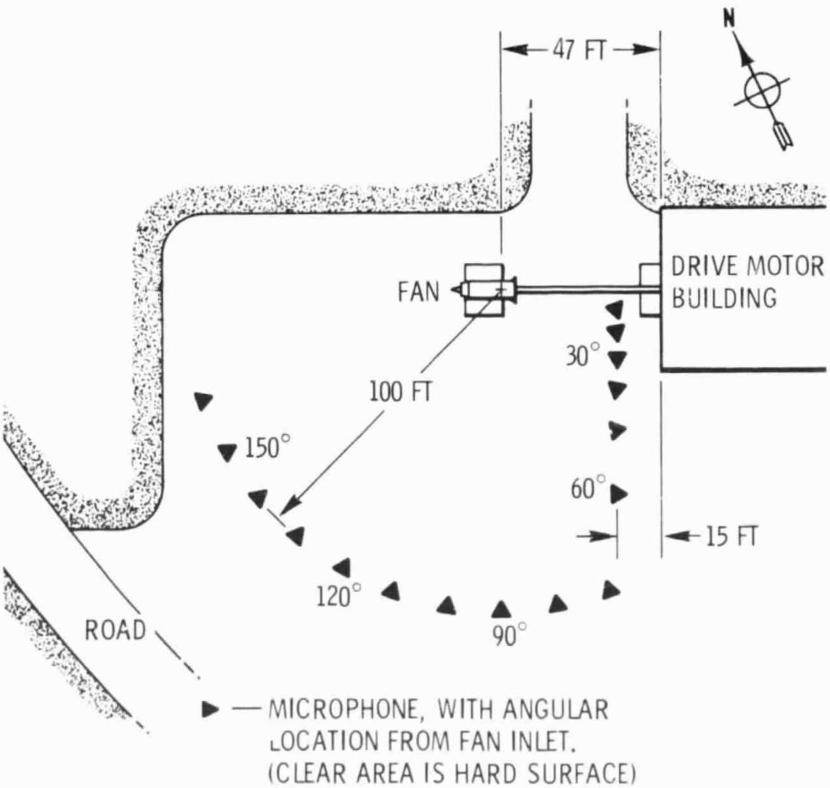


Figure 7. - Microphone locations for large-scale fan acoustic test facility.

E-5194

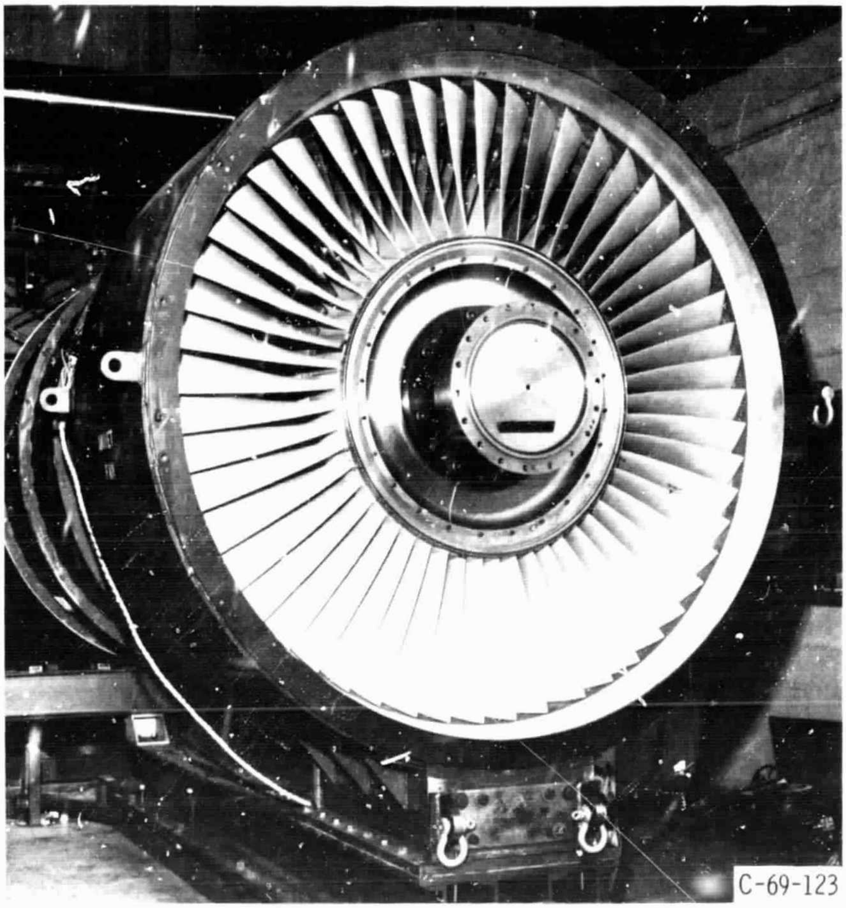


Figure 8. - Seventy-two-inch diameter single-stage fan rotor.

E-5194

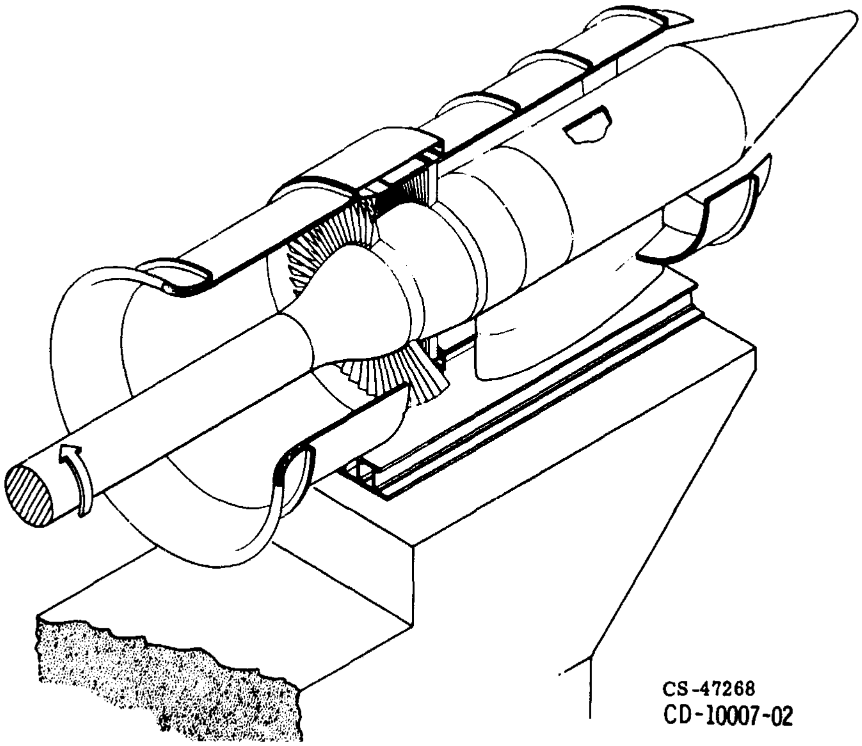


Figure 9. - Cross-sectional sketch of large-scale fan acoustic test facility.

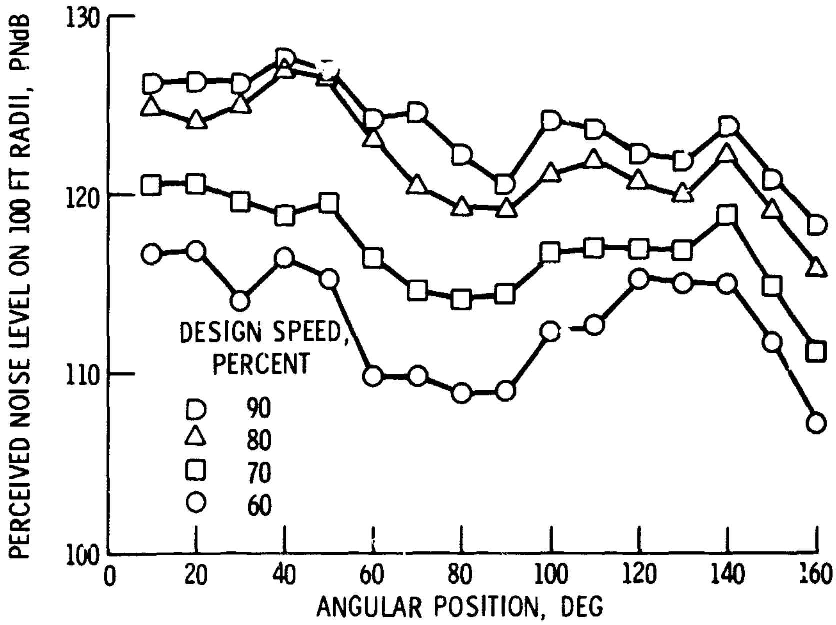


Figure 10. - Perceived noise level as a function of angular position (100 ft radius) about a single-stage fan.

E-5194

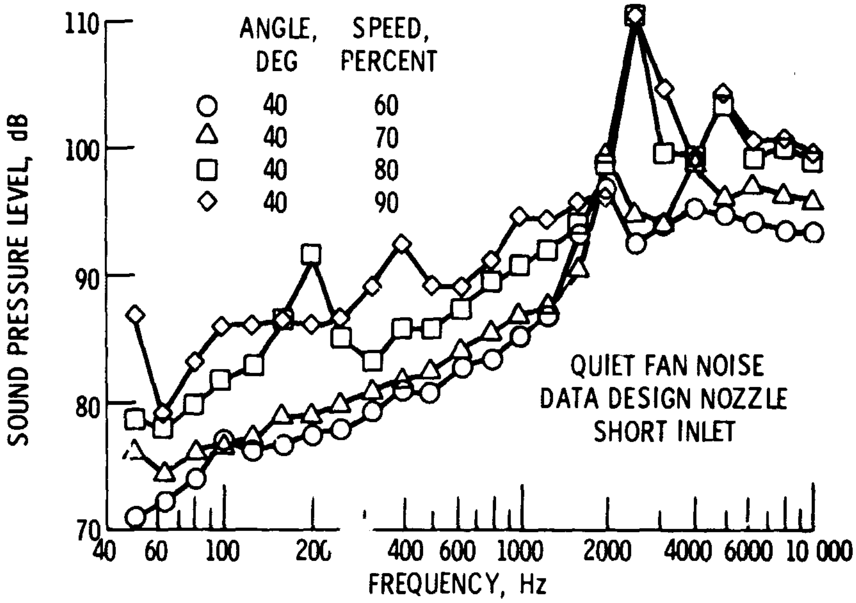


Figure 11. - Sound pressure level as a function of frequency (one-third octave bands) for a single-stage fan, 100 foot radius, 40° location (front quadrant).

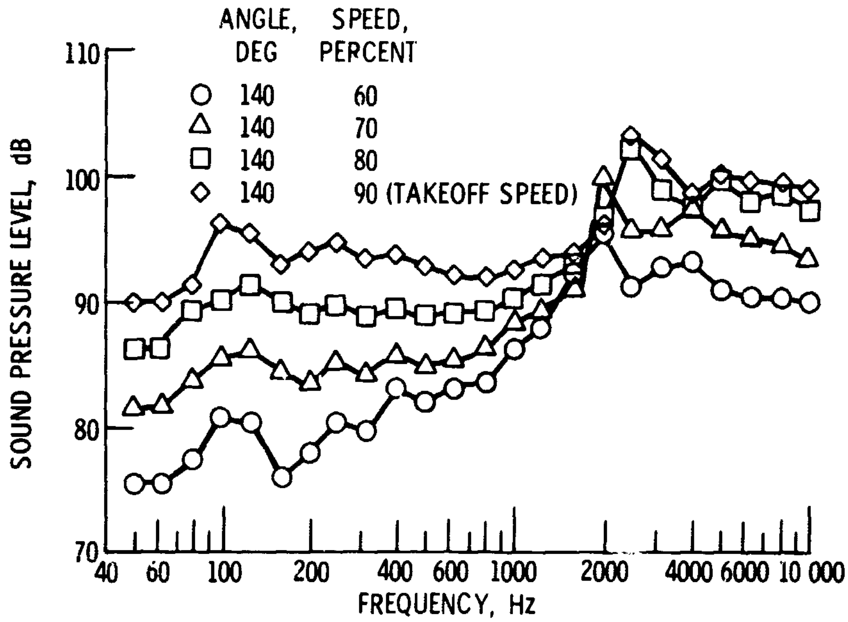
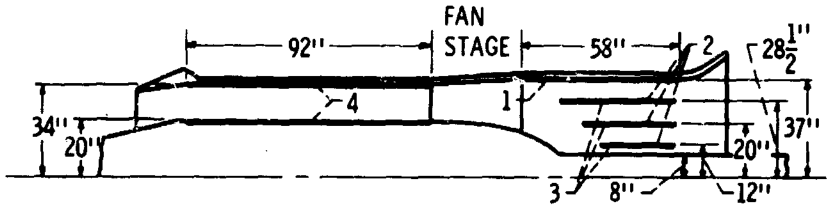


Figure 12. - Sound pressure level as a function of frequency (one-third octave bands) for a single-stage fan, 100 foot radius, 140° location (rear quadrant).

E-5194



	OPEN AREA RATIO, PERCENT	PLATE THICKNESS, IN.	HOLE DIA., IN.	BACKING DEPTH, IN.	HONEYCOMB
1	2.5	0.020	0.032	0.88	3/8 IN. HEX
2	2.5		.032	.20	
3	2.5		.032	.68	
4	8.0		.050	.88	

Figure 13. - Cross-sectional sketch of acoustically treated inlet and exhaust ducts for large-scale fan.

E-5194

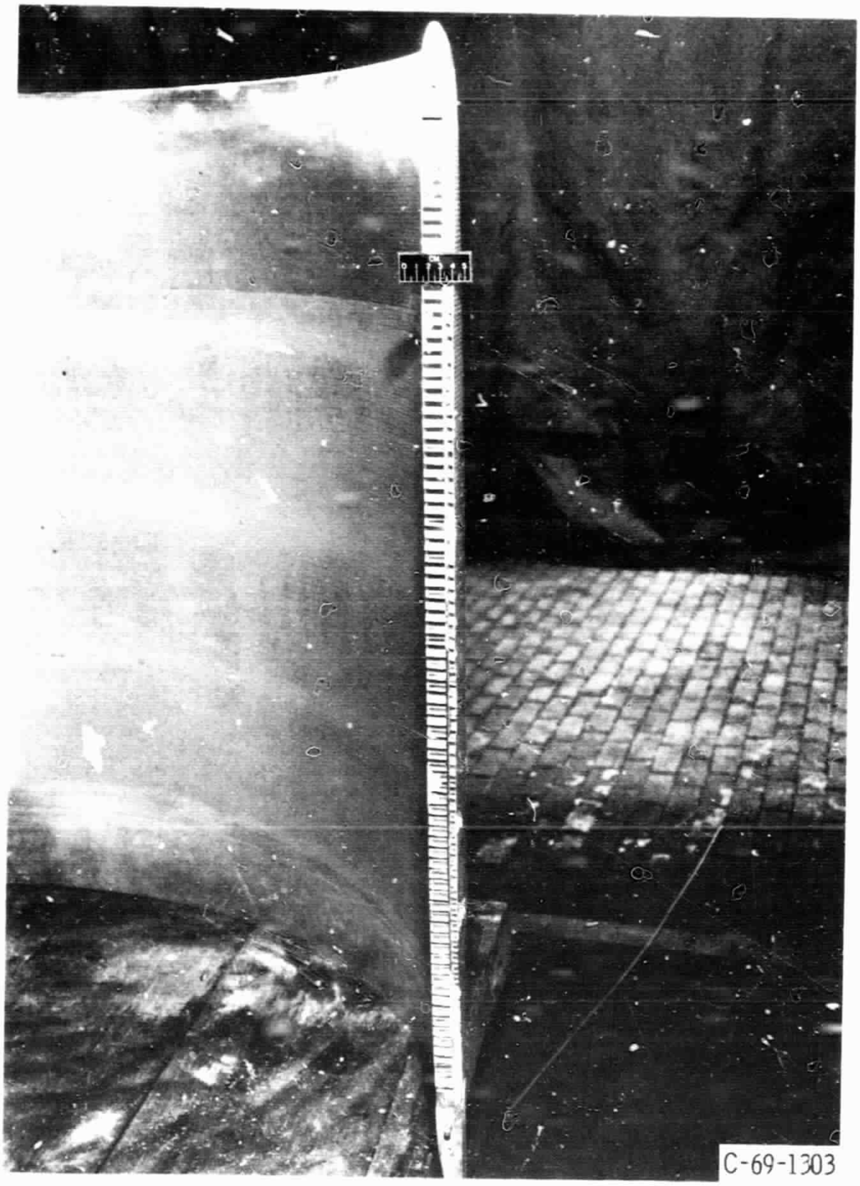


Figure 14. - Acoustic treatment on both sides of inlet splitter ring.

E-5194

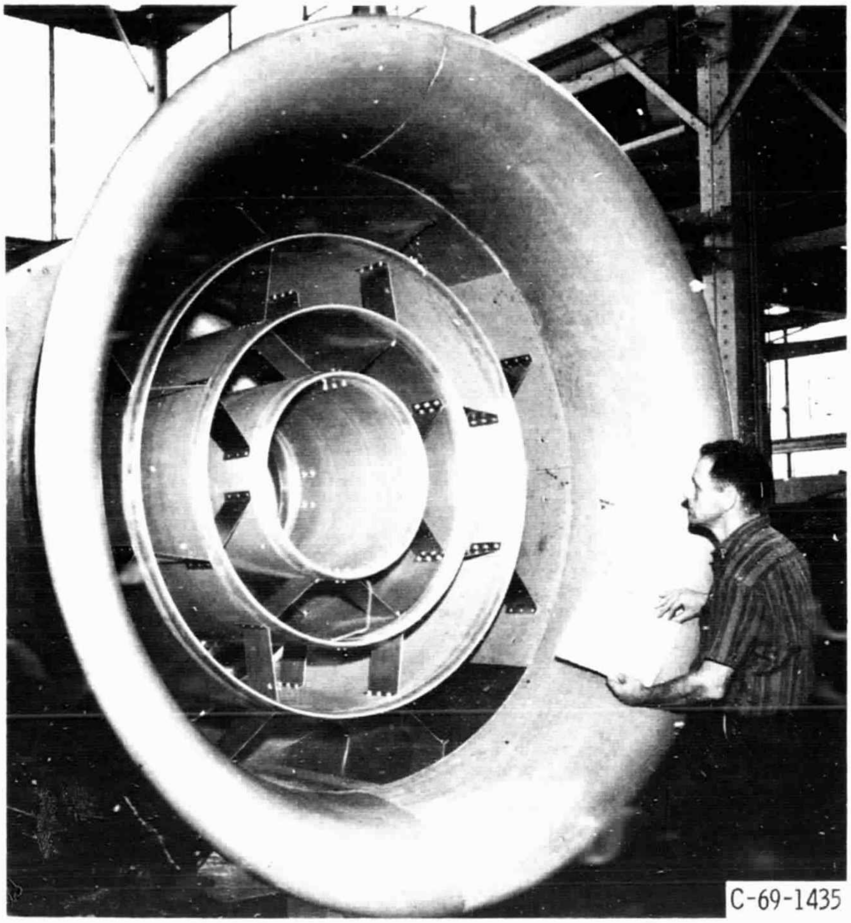
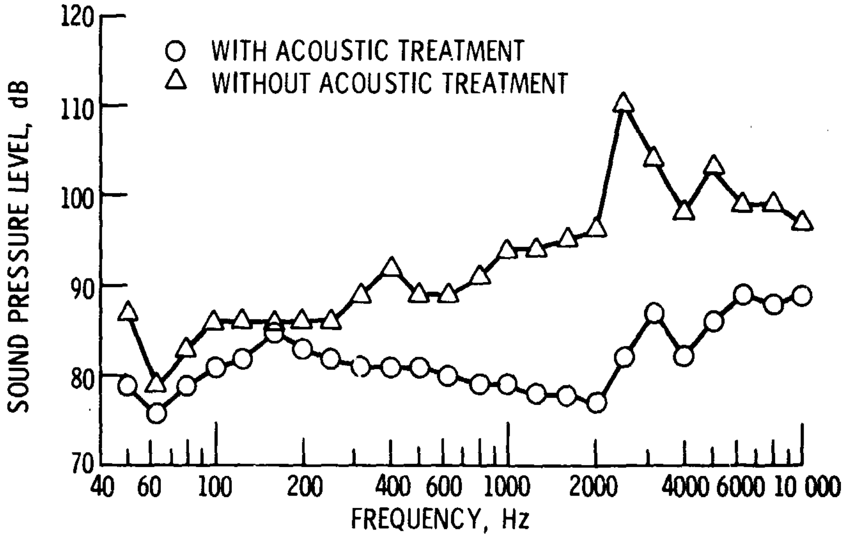


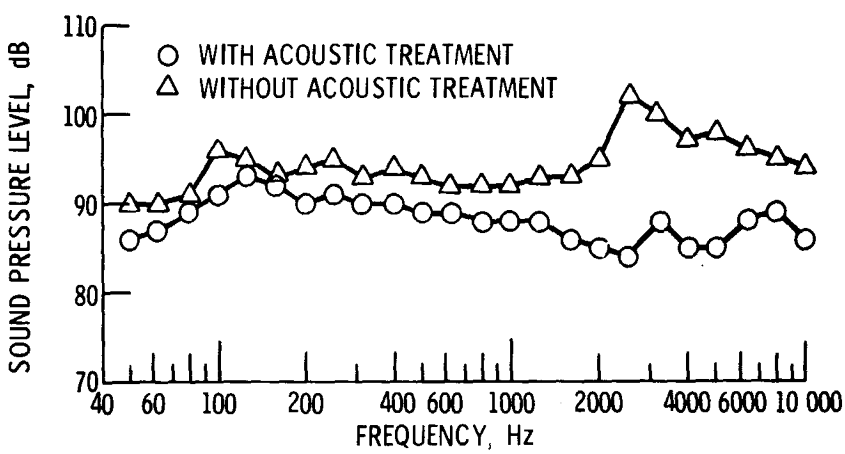
Figure 15. - Inlet duct with acoustic treatment.

E-5194



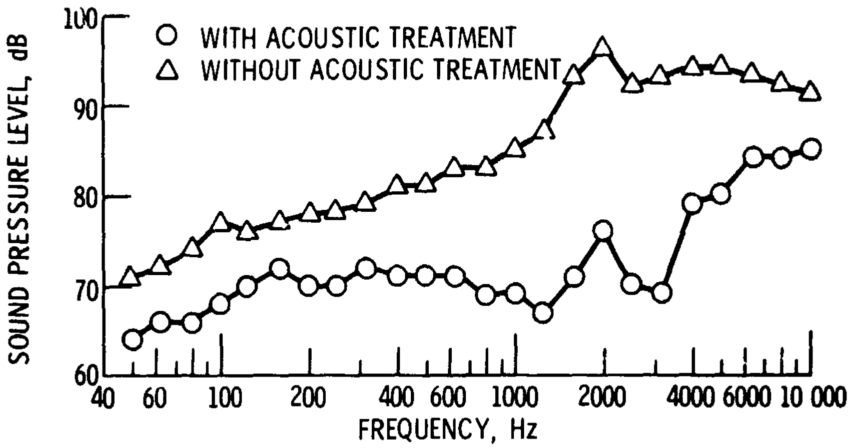
(a) Front quadrant (40°), takeoff fan speed.

Figure 16. - Sound pressure level as a function of frequency (one-third octave bands) for a single stage fan with and without acoustic treatment, 100 foot radius.



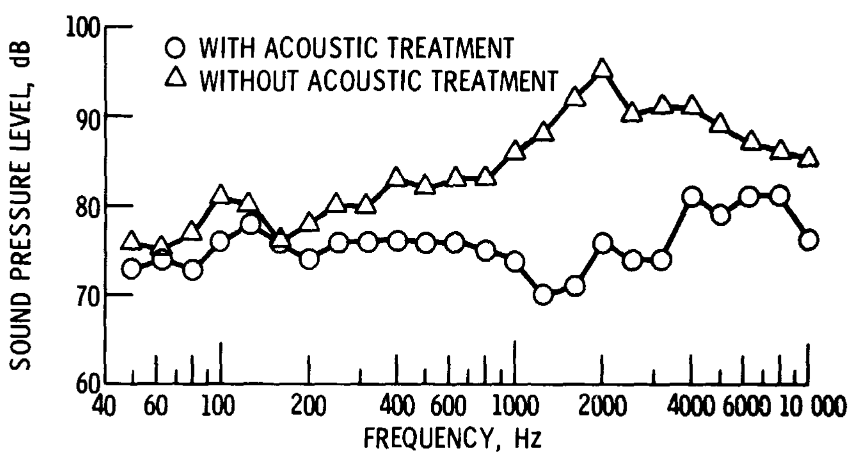
(b) Rear quadrant (140°), takeoff fan speed.

Figure 16. - Continued.



(c) Front quadrant (40°), approach fan speed.

Figure 16. - Continued.



(d) Rear quadrant (140°), approach fan speed.

Figure 16. - Concluded.